Anonymous Referee #1

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[GENERAL COMMENTS]

This paper presents the equatorial plasma pressure distributions obtained by the TWINS observation and by the drift kinetic simulation CIMI for the moderate storms of 7-10 September 2015. The general features of the plasma pressure in the inner mag- netosphere are similar to each other, whereas some differences are found in terms of peak location, anisotropy, and spatial distribution. The authors attributed the dif- ferences to the shielding effect and spatially-localized, short-duration injections of hot plasma.

The direct comparison between a sophisticated observation and an advanced drift kinetic equation is highly valuable, and is promising to overcome the difficulties arising from in-situ satellite observations. The provided data is basically very interesting, and I admire the authors' efforts to derive the pressure and anisotropy.

The authors thank the referee for the thoughtful and helpful comments. We respond positively below to each question and comment individually. Nevertheless, we cannot answer every question posed by referee with a full, unambiguous explanation. Such requires extensive investigations that are underway but are beyond the scope of this paper. We believe what many have said, i.e., good research raises at least as many questions as it answers.

Our responses are shown in bold font for ease of distinguishing our responses and the referee's comments.

However, I have 3 major concerns as follows:
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First, the physical interpretations made by the authors are unclear. Because of the lack of proper interpretations, I cannot catch new scientific knowledge or insights in the current version of the manuscript.

We certainly hope that our specific responses allow the referee and other readers to "catch new scientific knowledge or insights. . . "

Secondly, the reliability of the plasma pressure obtained by TWINS is also unclear. The spectral shape of the ion flux is almost the same at 4 different points, which seems unlikely to occur.

The intent of showing the spectral shapes in Figure 10 was not to present an extended discussion of the spectra but rather to indicate that were two peaks, one at low energy, i.e., below 20 keV, and a second near 40 keV and to illustrate why the paths of 40 keV particles are shown. We are not sure that this is unlikely to occur. Details of the magnitude and shape of the energy spectra will be addressed in an extensive study that is underway.

As to the overall reliability of the plasma pressure, that is a difficult question to answer definitively and quantitatively. In the description of the methodology used to obtain the ion pressure from the TWINS ENA images, we have referenced the extensive testing of the ion distributions obtained from

the TWINS ENA images. (See Section 2.2, lines 190 ff in the version of the paper where corrections are accepted and lines 194 ff in the version of the paper where corrections are marked.)

Thirdly, the plasma pressure mentioned in this paper is "partial" so that the "true" distribution of the plasma pressure would be different. Careful description is needed when the authors intend to say the distribution of the pressure.

The referee is correct. What we show in this paper are "partial" pressures. The intent is to have the TWINS and CIMI results consider as nearly as possible a similar energy range. In the revised paper, all references to the particular pressures from TWINS and CIMI are now designated as partial pressure.

[SPECIFIC COMMENTS]

1.On the interpretations. The authors concluded that the difference between the ob- servation and the simulation can be best explained by enhanced electric and magnetic shielding and/or spatially-localized, short-duration injections. First of all, please explain the meaning of the electric and magnetic shielding in more detail. Most of the readers may not understand the meaning of it. The electric shielding is supposed to result from the ionospheric electric field redistributed by the Region 2 field-aligned current.

Excellent suggestion. We include in the revised version anexplanation as to what we mean by electric shielding. [See Lines 436-445]

What is the magnetic shielding?

"magnetic shielding" was an improper term. Better to say enhanced electric field shielding and/or induction electric fields caused by spatially-localized, short duration injections. The term is omitted in the revised version.

What is the expected effect of the shielding on the pressure distribution and pressure anisotropy?

It has been demonstrated that the electric shielding can affect the ring current morphology. [See Lines 90-94 in the revised document.] The purpose of this paper is to show much more explicitly what are the expected effects. We are currently undertaking a project to couple the CIMI code in the inner magnetosphere with a 3D hybrid code that simulates the rest of the magnetosphere. We expect the results to address these issues in even greater detail.

CIMI/RCM takes into account the shielding. What physical processes or parameters does CIMI/RCM need to consider properly to explain the observations?

The CIMI simulations presented in this paper do not have localized injections into the inner magnetosphere. This has been demonstrated to have an effect on the pressure distributions. [See Lines 524-526 in the revised document.] While the CIMI simulations in this paper do include some contributions from induction electric fields, the Tsyganenko magnetic field is not updated on short enough time scale to capture all of the induction electric fields. We, of course, do not know whether the steps we are taking to provide localized and short term injection effects will answer all the questions.

Have the authors tested CIMI/RCM with different conditions/parameters to explain the observations?

There have been investigations that demonstrate that changing the input at the boundary of the CIMI simulations does impact the ring current morphology. Also it has been shown that injecting non-isotropic pitch angle distributions impacts the parameter of the ring current. [See Lines 507-509 in the revised document] The authors have not tried, however, to reverse engineer the input to the CIMI simulations presented in this paper to attempt to match the data.

(1) On reliability of the plasma pressure. In Figure 10, the differential fluxes of the ions are shown as a function of energy at 4 points. The intensity of the flux is different but the spectral shape is almost the same with each other. Why is the spectral shape of the flux almost the same at the 4 points? According to in-situ observations, the spectral shape of the flux depends on L-value and magnetic local time (e.g., Milillo et al., 2001, 10.1029/2000JA900158), so that it seems kquite unlikely to be the same spectral shape at 4 points. Please explain the validity of the spectral shape of the flux and the plasma pressure distribution presented in this paper.

We reference the published examples of validation of all the features of the ion distributions through comparisons with in-situ measurements. [See Lines 191-202.] These examples were chosen because the satellites happen to be in the right place at the right time to see the features of interest. It is true, of course, that such comparisons do not guarantee the complete validity of the current results.

The main reason for showing the measured energy spectra was to show why the paths of 46 keV ions were used to display the location and time of the injections of the ions that had 46 keV energy at the peaks. What the authors think has the relevant validity in this case is the high energy a low energy peaks in the spectra.

The outstanding work by Millilo et al , 2001 will make an important contribution to our current investigation into the details of the energy spectra during geomagnetic storms during the TWINS mission. The fact that the average results presented in their paper is for AE < 100 nT does not directly invalidate the results presented here.

Finally, as was stated above, the focus of this paper is not the details of the energy spectra. If the referee would prefer, we could remove them from Figure 10.

Secondly, please explain the expected effect of spatially-localized, short-duration injections on the pressure and anisotropy.

As described above and is illustrated to some extent in previously referenced work, the authors expect that spatially-localized, short-duration injections will impact the spatial and temporal locations of the pressure peaks. We also expect it to be a key factor in explaining the observation of multiple peaks in the ring current.

Have the authors modeled spatially-localized, short-duration injections to explain the observations?

As stated above, it has been demonstrated that spatially localized injections can affect the ring current morphology, but we have not tried to match the observations for this particular storm without some experimental or theoretical guidance. There is an ongoing investigation to couple CIMI with a 3D hybrid simulation of the injections from the tail explicitly intended to address this question.

Thirdly, please explain the reason why the CIMI result always shows parallel anisotropy of the plasma pressure in the dawn-midnight-dusk region. The pressure anisotropy is largely different from the observations. Detailed explanation is needed.

An explanation is given in the revised paper. [See Lines 490-496 in the revised document.] Whether this is the complete explanation is uncertain at this time. The authors expect to develop a more definitive explanation as part of an ongoing investigation to couple CIMI with a 3D hybrid simulation of the injections from the tail.

(2) On the plasma pressure. I suppose that the plasma pressure was calculated from integration of the differential flux over the energy range from 2.5 keV to 97.5 keV. The energy range is probably insufficient to cover all the ions trapped in the inner mag- netosphere because the ions with energy greater than 100 keV is also known to con- tribute to the plasma pressure (energy density) largely (e.g., Smith and Hoffman, 1973, 10.1029/JA078i022p04731; Williams, 1983, 10.1016/0032-0633(81)90124-0). If the high energy ions remained during these storms, there would be another peak of the pressure, which may stay at L ~ 2.5 – 3.0. I recommend discussing possible impacts of the high energy ions (>100 keV) on the conclusion. I also recommend emphasiz- ing that the plasma pressure distribution is "partial" so that the pressure distribution is incomplete.

The referee is correct, the plasma pressure presented in this paper should be referred to as partial pressure because it was calculated by integrating from 2.5 to 97.5 keV. The paper by Smith and Hoffman, 1973 certainly shows that higher energies can make significant contributions to the energy density (pressure). It is to be noted, however, that they say

“To contrast the development of the ring current for the two storms, we now consider those protons (1- to 138-kev protons were used) which contribute substantially to the storm-time ring current. While protons in this energy regime contribute only 20% or less to the total energy density out to L -• 4 during magnetically quiet periods, their enhancement during magnetic storms, combined with a depletion of protons with energies greater than about 170 kev, make them the dominant (greater than 90%) contributors to the storm-time energy densities.”

The paper is referenced. [See Line 179 in revised document.)

The paper by William, 1983, describes the state of observations at that time with the conclusion, “It is found that the ring current energy density composition still has not been observed.”

The authors wholeheartedly agree with the recommendations of the referee.

[MINOR COMMENTS]

Introduction: I recommend citing papers related to plasma pressure distribution and anisotropy observed by satellites, for example, De Michelis et al. (1999, 10.1029/1999JA900310), Ebihara et al. (2002, 10.1029/2002GL015430), and Lui (2003, 10.1029/2003GL017596).

Definitely. The authors apologize for not recognizing these papers. [See Lines 65, 70, 72 in revised document.]

Line 47-57: Simulation results with different electric field and/or magnetic field models have been conducted by Angelopoulos et al. (2002, 10.1029/2001JA900174) and Ebihara et al. (2004, 10.5194/angeo-22-1297-2004).

Most definitely. The authors thank the referee for pointing us to these papers. [See Lines 55, 61 in revised document.]

Line58-63: This paragraph seems not to provide information. What key spatial features do Wang et al. (2011) find?

The authors think it is somewhat harsh to say that the paragraph [Lines 65- does not provide any information. In particular reference to the Wang et al. (2011) paper, the paper presents extensive data and comparisons with RCM modeling, but they are based upon statistical averages of events. The result from Wang et al (2011) that is relevant to this paper is what is stated in the last sentence of this paragraph. It is based upon the last sentence of the Abstract and the first sentence of the Summary.

Line 311: The equatorial pressure p_eq is difficult to understand. Please explain how to derive p_eq.

The authors are not sure why p_eq is difficult to understand. It is pressure at the equator as a function of position and pitch angle. It is the standard definition of pressure, i.e., the energy density of the ions, the integral of the distribution function times the velocity squared.

What follows is an exchange between the referee and the authors that clarified the original equations. The referee's comments are shown in different colors reflecting the order in which they entered the discussion. The authors responses are in bold black. The paragraph now reads as shown in Lines 333-340 of the revised document.

The authors answered my comments properly except for one thing on the equatorial pressure (Line 311 in the first version of the manuscript). The authors stated that peq is pressure at the equator as a function of position and pitch angle, and that it is the standard definition of pressure. If it is the standard definition of pressure, please cite relevant reference. The reason why I am asking is that readers may be eager to know how the authors obtained the terms,P⊥ and P||. Here, I assume that P⊥ and P||are the pressure tensor components in the perpendicular and parallel components, respectively. Lui et al. (1987, 10.1029/JA092iA07p07459) show the equations to calculate P⊥ and P|| as a function of velocity v and the velocity distribution function f (Eqs. 2 and 3 in Lui et al., 1987). The velocity distribution function f is associated with the differential flux that is directl ymeasurable. What is the relationship between peq and the measured value (probably differential flux derived from the ENA observation)?

The Referee is correct, the equation as presented is unclear. Somehow the full response to the original comment was lost.

The pressure anisotropy shown in Figure 3 is defined as

$$A = \frac{P_\perp - P_\parallel}{P_\perp + P_\parallel}$$

with

$$P_\perp = \int_{-1}^{+1} p_{eq}(\alpha)\sin^2\alpha \; d\cos\alpha \quad \& \quad P_\parallel = 2\int_{-1}^{+1} p_{eq}(\alpha)\cos^2\alpha \; d\cos\alpha$$

where α is the pitch angle and p_{eq} is the equatorial pressure as a function of location and pitch angle which was obtained from the energy dependent number flux deconvolved from the TWINS ENA images, i.e.,

$$p_{eq} = \frac{2\pi}{m}\int_0^\infty E\ f(E,n,\cos\alpha)\,dE$$

where $f(E,n,\cos\alpha)$ is the number of ions per unit area, energy, and steradian. This definition is derived from Braginskii (1965) and is consistent with previous formulations, e.g., Lui et al. (1987).

The authors now present the meaning of the equatorial pressure peq as peq = 2π mREfde, where m is mass, E is energy, and f is the number of ions per unit area, energy and steradian. First of all, I am unsure if f corresponds to the so-called differential number flux that is the number of ions per unit area, energy, time and steradian. If so, I have further comment. The definition of the perpendicular and parallel pressure (P⊥ and P||) is as follows. P⊥ = 1 2Rmv2 sin2 αFdv and P|| = Rmv2 cos2 αFdv, where F is the velocity distribution function. These equations can be derived from the original definition of pressure (probably Braginskii (1965) provided, too). Lui et al. (1987) also present these equations. The velocity distribution function is given by F = m v2 f. Substituting this into above equations, I have P⊥ = RRπ√2mf√E sin2 αd(cosα)dE = RRπ√2mf√EdE sin2 αd(cosα) = Rpeq sin2 αd(cosα)and P|| =RR2π√2mf√E cos2 αd(cosα)dE =R2peq cos2 αd(cosα), where peq =Rπ√2mf√EdE. It seems that the definition of peq is different from the authors'. The same equation is found in Eqs (7) and (8) in De Michelis et al. (1997, doi:10.1029/96JA03743). Maybe I misunderstand, but I would like to make it clear. I suggest avoiding the term 'equatorial pressure' because this term is confusing and misleading. The above equations can be applied for everywhere, not restricted in the equatorial plane.

The question seems to revolve around 2 areas of confusion.

First, the use of the subscript "eq" to indicate that it is the equatorial pressure. The purpose was to communicate that it is at the equator that we actually calculate the pressure anisotropy. We agree, however, that this may be confusing so we agree to leave it out.

Second the definition of the symbols *f* and *F* in the equations. We suggest that to try to avoid this confusion, we suggest the following:

The pressure anisotropy shown in Figure 3 is defined as

$$A = \frac{P_\perp - P_\parallel}{P_\perp + P_\parallel}$$

with

$$\begin{Bmatrix} P_\perp \\ P_\parallel \end{Bmatrix} = \int_{-1}^{+1} d\cos\alpha \begin{Bmatrix} \sin^2\alpha \\ 2\cos^2\alpha \end{Bmatrix} \left(\int_0^\infty dE \sqrt{\frac{2E}{m}} F(E,n,\cos\alpha) \right)$$

where *α* is the ion pitch angle, *E* is the ion energy, *n* is the ion density, *m* is the ion mass and *F(E,n,cos α)* is the number flux per unit area, energy, time, steradian. This definition is derived from Braginskii (1965) and is consistent with previous formulations, e.g., Lui et al. (1987).

The authors revised the equation for the pressure terms. However, the equation seems to be different from the equation given by De Michelis et al. (1997, http://doi.wiley.com/10.1029/96JA03743) by a factor of πm. I am curious to know the reason why the equation is different. The definition of the plasma pressure is changed. Does this change have any impact on the result? I suppose that lower energy protons may have more impact on the pressure. I recommend removing n from F(E,n,cosα) because F is an arbitrary function and n is an independent variable.

We very much appreciate the comments that have been made by the Referee. They have certainly made our paper better. But at this time, it seems that we having trouble communicating. We are not sure how to respond. Please see comments below: (The Referee's comments are repeated in italics.)

The authors revised the equation for the pressure terms. However, the equation seems to be different from the equation given by De Michelis et al. (1997, http://doi.wiley.com/10.1029/96JA03743) by a factor of πm. I am curious to know the reason why the equation is different.

I assume that the referee is referring to Eqs. (7) and Eqs (8) in De Michelis et al. (1997). Let's look at the unit of those eqs. For the pressure to have the correct units of energy per unit volume, the units of the "differential flux intensity", *J* in Eqs. (7) and (8) must be 1/(vol * m * v). The reason for the different factors is that *J* is not the flux we have in our equation. Our flux, *F(E,n,cosα),* as it says in the text, has units of #ions/(energy*time*area*steradian). One can check the units of the equation we have in the paper and they come out to be pressure. In fact if one substitutes the proper equation for a Maxwellian distribution into the equation in the paper, i.e.,

$$F(E,n,\cos\alpha) = \frac{n}{\sqrt{2m}(\pi T)^{3/2}} E\, e^{-E/T}$$

and performs the integrals, the result is *nT* , precisely what one expects for a Maxwellian.

The definition of the plasma pressure is changed***.***

The definition of the plasma pressure has not changed. We have been discussing a general definition of pressure. That has not changed, just the way it is presented has been made clearer with the help of the Referee.

Does this change have any impact on the result? I suppose that lower energy protons may have more impact on the pressure***.***

We assume this is in reference to the previous comment regarding the change in the definition of the pressure. We assume that the referee is referring to the fact that the pressure we calculate and present as results is the partial pressure, i.e., it is integrated from 2.5 to 97.5 keV for TWINS and 1 to 133 keV for CIMI. The referee correctly requested that we distinguish the pressure calculated in this paper as the partial pressure and we have done so. There is no change that would impact the results in this paper.

I recommend removing n from F(E,n,cosα) because F is an arbitrary function and n is an independent variable.

This comment may somehow be at the heart of the miscommunication that we are having at this time. Yes, it is in some sense arbitrary, i.e., in the expression for the pressure, it is whatever it is in a particular physical situation. In what we are presenting, however, the *F(E,n,cosα)* is definitely not an arbitrary function. For the TWINS results, it is what is obtained from the ENA images. For CIMI, it is what is obtained from the simulations. As stated above it has units of #ions/(energy*time*area*steradian). We feel that it makes the most sense to express the pressure in terms of what it is obtained, i.e., from the measurements and simulations. It is then integrated as expressed in the formulas to obtain the pressures we present. We might also note that previous publications of TWINS and CIMI results have shown the average of *F(E,n,cosα)* over pitch angles as a function of energy.

My comment is simple: How did the authors calculate the plasma pressure? The following is the procedure that I am currently understanding. First of all, please make sure if my understanding is correct.

1. For the TWINS results, the authors obtained the differential flux F from ENA images. For CIMI, the authors calculated the differential flux F. F has units of the number of ions/(unit energy·unit time·unit area·unit solid angle).

Yes that is correct.

2. Theauthorscalculatedthepressuretermsbyintegrating F withrespecttoenergy and pitch angle.

P⊥ =Z dcosαsin2 αZ dEr2E m

F, (1)

P|| = 2Z dcosαcos2 αZ dEr2E m

F. (2)

We can only apologize to the Referee. There was a typing error in the equations we sent in our previous reply. The factor in the integral should be $\sqrt{2mE}$. There also is a factor of 2π from the integral over the gyrotropic angle. The paragraph in the proposal is now

The pressure anisotropy shown in Figure 3 is defined as

$$A = \frac{P_\perp - P_\parallel}{P_\perp + P_\parallel}$$

With

$$\begin{Bmatrix} P_\perp \\ P_\parallel \end{Bmatrix} = 2\pi \int_{-1}^{+1} d\cos\alpha \begin{Bmatrix} \sin^2\alpha \\ 2\cos^2\alpha \end{Bmatrix} \left(\int_0^\infty dE\, \sqrt{2mE}\, F(E, n, \cos\alpha) \right)$$

where *α* is the ion pitch angle, *E* is the ion energy, *n* is the ion density, *m* is the ion mass and *F(E,n,cos α)* is the number flux per unit area, energy, time, steradian. This definition is derived from Braginskii (1965) and is consistent with previous formulations, e.g., Lui et al. (1987).

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The units are now $steradians * E\sqrt{m^2v^2}\,\frac{1}{El^2t * steradians} = E\,\frac{mv}{mv^2t} = \frac{E}{l^3}$ **, i.e., energy/vol as it should be.**

Now, I realized that the confusion comes from the definition of F.

That is exactly correct.

Eqs. (1) and (2) will be understandable if F is the velocity distribution function, NOT differential flux!

I am not sure what you mean by "differential flux". It is my understanding that one can have energy flux, number flux, charge flux, etc either per velocity, per energy, etc.

It is true that *f* is often the used for the velocity distribution function. That is not what *F* is the equation above and in the paper.

The velocity distribution function, which is the number of particles in 6-dimensional space, is defined by

F = m2 2Ej.

Using this relationship, Eqs. (1) and (2) yield P⊥ =Z dcosαsin2 αZ dE√2Emj, (3) P|| = 2Z dcosαcos2 αZ dE√2Emj. (4) Eqs. (3) and (4) are consistent with Eqs. (7) and (8) of De Michelis et al. (1997) who use the symbol J to represent the differential flux.

Yes, the corrected equations above are exactly as you say. If all that is needed to make it clear is to change *F* to *j*, we have no problem with that.

Hereinafter, I would like to define the terms F and j to be the velocity distribution function and the differential flux, respectively, to avoid confusion. I would appreciate if the authors make sure which equations, (1)-(2), or (3)-(4), the authors used to calculate the pressure.

We want the function in the integral to per unit energy. That is not what we would call a "velocity distribution".

In the second reply, the authors stated that the plasma pressure was calculated by P⊥ =Z peqdcosαsin2 α, (5) P|| = 2Z peqdcosαcos2 α, (6) peq = 2π mZ EjdE. (7) Although Eqs. (5)-(7) are different from Eqs. (1)-(2) and Eqs. (3)-(4), the authors state that the change of the equations does not affect the results. Why? Does it mean that the authors did not use these equations to calculate the pressure? Does Eqs. (5)-(7) include typographical error?

Honestly, we do not remember an equation of mine with a *j* in it. We would not say that Eqs. (5-6) contain typographical errors. We would say they were ill-defined and unclear. We appreciate your efforts to make them clear. At this point, we think that they are at least well- defined and describe appropriately the equations we used to calculate the anisotropy measurements and simulations we report in the paper.

I may misunderstand something, but I would appreciate very much if the authors answer these questions.

Given the unclear definitions we presented originally and the mistakes made in the equation we sent in our earlier reply, it is reasonable that you have not understood. To the best of our knowledge, the equations are now correct and well-defined.

To summarize, we want to use #ions per unit energy*area*time*steradians in the integral definition of the parallel and perpendicular pressure.

We have tried and will gladly continue to try to answer your questions until you are satisfied.

Line 489-496: Ebihara et al. (2009) also showed multiple peaks of the plasma pressure distribution in the inner magnetosphere by introducing temporal changes in the distribution function at the outer boundary of CRCM. It would be worth mentioning that the rapid changes in the distribution function in the plasma sheet could result in the multiple peaks of the plasma pressure**.**

A sentence has been added pointing out that the model calculations did show multiple pressure peaks inside of 4 R_E. [See Lines 534-535 in revised document.]

Line 499 "But they do not provide incontrovertible evidence for the effects of spatially and temporally dependent injections into the inner magnetosphere." This sentence is difficult to understand.

The sentence has been removed.

Figure 10, caption: Please indicate the unit of the color bar (probably in keV), and pitch angle of the particle. What is the meaning of "Minimum – Maximum Energy for Each Path"?

An explanation has been added. [See Figure 10 caption, Line 1035 of revised document.]

Line 520, "Peak 5" Does it mean "Peak 4"?

Yes. It has been corrected. [See Line 563 of revised document.]

Line 497-527: The spectral shape of the differential flux of the ions is almost the same at the 4 points. Please explain the validity of the differential flux derived from TWINS? At Peak 3, the ion is inaccessible from the outer boundary. I recommend tracing the ion trajectory backward in time by starting at slightly different points.

I think we have addressed this issue in response to previous comments. The main reason for presenting these spectra is to motivate showing the paths of the 46 keV ions. As stated above, if the referee prefers, they can be removed.

Line 546-548: "This is not unexpected as the ions are being injected into regions of higher magnetic field, and conservation of the first adiabatic invariant would predict the enhancement of parallel pitch angles." I cannot understand this meaning. Please explain the reason why the conservation of the first adiabatic invariant results in the pressure anisotropy dominated by the parallel component?

A full explanation has been added. [See Lines 589-598 in revised document.]

Line 548-550: "Nevertheless the parallel anisotropy is seen in the observations only during the main phase of the first storm. This is also an indication of stronger electric and magnetic shielding." Please explain the reason why the stronger shielding results in the parallel anisotropy?

The statement has been changed to be consistent with responses to previous comments by the referee. [See Lines 589-598 in revised document.]

The authors answered my question properly. Everything is now clear. I have no additional comments or concerns. I recommend this paper for possible publication in Annales Geophysicae

Dynamics of a Geomagnetic Storm on 7-10 September 2015 as Observed by TWINS and Simulated by CIMI

Perez[1], Joseph D., James Edmond[1], Shannon Hill[2], Hanyun Xu[1], Natalia Buzulukova[3], Mei-Ching Fok[3], Jerry Goldstein[4,5], David J. McComas[6] and Phil Valek[4,5]

[1]Auburn University, Auburn, AL 36849, USA
[2]Emory University, Atlanta, GA 30322, USA
[3]NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
[4]Southwest Research Institute, San Antonio, TX 78228, USA
[5]University of Texas at San Antonio, San Antonio, TX 78249, USA
[6]Department of Astrophysical Sciences, Princeton University, NJ 08540, USA

Correspondence to: J. D. Perez, perez@physics.auburn.edu

Abstract. For the first time, direct comparisons of the equatorial ion partial pressure and pitch angle anisotropy observed by TWINS and simulated by CIMI are presented. The TWINS ENA images are from a 4-day period, 7-10 September 2015. The simulations use both the empirical Weimer 2K and the self-consistent RCM electric potentials. There are two moderate storms in succession during this period. In most cases, we find that the general features of the ring current in the inner magnetosphere obtained from the observations and the simulations are similar. Nevertheless, we do also see consistent contrasts between the simulations and observations. The simulated partial pressure peaks are often inside the observed peaks and more toward dusk than the measured values. There are also cases in which the measured equatorial ion partial pressure shows multiple peaks that are not seen in the simulations. This occurs during a period of intense AE index. The CIMI simulations consistently show regions of parallel anisotropy spanning the night side between approximately 6 and 8 R_E whereas the parallel anisotropy is seen in the observations only during the main phase of the first storm. The evidence from the unique global view provided by the TWINS observations strongly suggests that there are features in the ring current partial pressure distributions that can be best explained by enhanced electric shielding

and/or spatially-localized, short-duration injections..

Key Words. Magnetospheric physics (Storms and substorms, Magnetosphere configurations and dynamics) **–** Space plasma physics (charged particle motion and acceleration)

1 Introduction

The Earth's inner magnetosphere contains a large-scale current system, the ring current, in which the current is carried by trapped ions that are injected from the magnetotail and generally drift westward. It is a major contributor to magnetic depressions measured in the Earth's equatorial region that are expressed in terms of the Dst or SYM/H indices which characterize the time-evolution of geomagnetic storms. The plasma sheet is a primary source of particles in the inner magnetosphere. Therefore understanding and predicting the dynamics of the injected particles is a key factor in understanding the formation and decay of the ring current. This challenge can be addressed by a comparison of model and simulation results with observations.

There have been many studies which compared model results to observations. Kistler and Lawson (2000) used 2 different magnetic field models, dipole and Tsy89 (Tsyganenko, 1989), along with two different electric potential models, Volland (Volland, 1973)-Stern (Stern, 1975) and Weimer96 (Weimer, 1996), to calculate ion paths in the inner magnetosphere. They compared the results with in-situ proton energy spectra measured by the Active Magnetospheric Particle Tracer Explorers (AMPTE) (Gloeckler et al, 1985) over a range of local times. They found that, in the inner magnetosphere, the electric field has a much stronger effect on the particle paths than the magnetic field and that the Weimer96 model gave a better match to the features of the observed energy spectra than the Volland-Stern model. But the energy at which the drift paths became closed, 40-50 keV, was not in agreement with the observations. It is to be noted that the effects of induction electric fields were not included in this analysis. Angelopoulos et al. (2002) added co-rotation electric fields to Volland-Stern, Weimer 96, Weimer 2000 along with modifications to improve fits to instantaneous electric field measurements by POLAR/HYDRA (Scudder et al., 1995) and Defense Meteorological Satellite Program satellites to compare with in-situ measurements of ion spectrograms from POLAR/HTDRA , EQUATOR-S (Kistler et al., 1999) and FAST (Carlson, et al., 2001). They found differences that seemed to require the inclusion of local inductive electric fields and/or particle injections. Ebihara et al., (2004) modeled discrete energy bands observed by POLAR using a dipole magnetic field and a realistic electric field to show that changes in the convection electric field produced better results.

De Michelis et al (1999) obtained images of pressure in the equatorial plane, both orthogonal and parallel, and anisotropy using 2-year averages of proton distributions measured by AMPTE/CCE-CHEM (Dassoulas et al., 1985; Gloeckler et al., 1985). They located 2 current systems, the inner portion of the cross-tail current and the ring current during times of AE > 100 nT, and both the full and partial ring current along with region 2 currents for 100 nT < AE < 600 nT. Ebihara et al. (2002) compared statistically averaged data from POLAR/MICS (Wilken, et al., 1992) with simulations of proton drift paths using the Volland-Stern electric potential and found reasonable agreement. Lui, et al. (2003) used the AMPTE/CCE-CHEM and MEPA (McEntire et al., 1985) to construct the plasma pressure distribution over an extended energy range from 1 keV to 4 MeV. They found that the statistical pressure distribution obtained from the in-situ measurements differed from the results obtained from ENA images obtained from IMAGE/HENA (Brandt et al., 2004). Wang et al (2011) compared average spatial profiles of the

Time History of Events and Macroscale Interaction during Substorms (THEMIS) (Angelopoulos, 2008) in situ-observations with simulations using the Rice Convection Model (RCM) self-consistent electric and magnetic fields (Toffoletto et al, 2003). The agreement with key spatial features of the particle fluxes confirms the importance of the magnetic and electric transport in determining features of the ring current. With the advent of missions dedicated to energetic neutral atom (ENA) imaging, e.g., (1) the 3 instruments, LENA (T. E. Moore et al, 2000), MENA (Pollock et al, 2000), and HENA (Mitchell et al, 2000) on board IMAGE (Burch, 2000), (2) the Energetic Neutral Atom Detector Unit (NUADU) (McKenna-Lawlor et al, 2005), and (3) Two Wide-angle Imaging Neutral-atom Spectrometers (TWINS) (McComas et al, 2009a; Goldstein and McComas, 2013; Goldstein and McComas, 2018), it became possible to test simulations against full images of the inner magnetosphere.

Fok et al (2003) compared simulations using the CRCM (Fok et al, 2001) model with ENA images from IMAGE/MENA & HENA. They were able to match the magnitude and trends of the observed Dst but not all of the short time variations. The empirical Weimer96 electric field model was not able to explain the fact that the peaks of the proton flux in the inner magnetosphere were in the midnight/dawn sector rather than the expected dusk/midnight sector during a strong storm on 12 August 2000, but the self-consistent CRCM electric field model did explain this feature. They also used the MHD fields computed by the BATS-R-US (Block-Adaptive-Tree Solar-wind Roe Upwind Scheme) (Groth et al, 2000) model to provide electric and magnetic fields and ion temperature and density at the model boundary (10 R_E) at the equator to model a large storm that occurred on 15 July 2000. The simulated ENA images matched the general features of the HENA ENA images.

Buzulukova et al. (2010) studied the effects of electric shielding on ring current morphology by comparing the results of CRCM simulations from a moderate and a strong storm with ENA images from TWINS and IMAGE/HENA. The Tsy96 empirical magnetic field, the Weimer-2000 electric potential model (Weimer, 2001) and the empirical Tsyganenko amd Mukai (2003) model of the plasma sheet density and temperature were employed. They achieved agreement between the magnitude and trends of the observed SYM/H and the simulated values for both storms, and were able to explain the post-midnight enhancements of the pressure due to electric shielding. They did not include the effects of inductive electric fields or time dependence due to substorms.

Fok et al (2010) used ENA images from both TWINS1 and TWINS2 along with in-situ THEMIS observations during a storm on 22 July 2009 to validate the CRCM simulations. They found that, when a time-dependent magnetic field is included, the electric potential pattern is less twisted and the ion flux peak did not move as far eastward giving better agreement with the ENA observations.

It is clear that present-day simulations are able to explain the general features of the observations of the ring current in the inner magnetosphere, both from in-situ measurements and in ENA images. It is also clear that questions remain as to the contributions of various shielding mechanisms. Self-consistent dynamic electric potentials give better results. Inclusion of magnetic induction effects is also necessary for the best results. But to date effects on short time scales, e.g., injections from sub-storms, bubbles, and bursty bulk flows have not been included in a self-consistent manner.

It is also important to note that the cases treated have been either statistical averages or single events in which there was no evidence for multiple peaks in the ring current pressure distribution. The existence of multiple peaks, however, has been observed in data from the AMPTE Charged Particle Explorer mission (Liu et al, 1987; Ebihara et al, 1985) and in ion distributions extracted from TWINS ENA images (Perez et al., 2015).

The science question to be addressed by this study is: Are there features in the global ring current pressure that are caused by enhanced electric shielding and/or spatially-localized, short-duration injections? We present for the first time a direct comparison between simulations of ring current equatorial partial pressure and anisotropy distributions with the unique global images extracted from the TWINS ENA images. We present cases in which the general characteristics of the observed partial pressure distribution are reproduced by the simulations and others in which the observed ion partial pressure peaks are at larger radius, in different MLT sectors, and display multiple peaks that are not found in the simulations. We also compare for the first time global images of the pressure anisotropy extracted from the TWINS ENA images with the results of simulations using the Comprehensive Inner Magnetosphere Ionosphere (CIMI) model (Fok et al., 2014).

In Sect. 2, we describe the measurement of the TWINS ENA images and the process by which ion partial pressures and anisotropy are extracted, and briefly discuss how this technique has been validated against in-situ measurements. In Sect. 3, we describe the important aspects of the CIMI model, and how it has been compared with geomagnetic activity indices, in-situ measurements, and ENA images. The particular storms on 7-10 September 2015, which are the focus of this study, are described in Sect. 4. The comparison of results of the measurements and simulations are presented in Sect. 5. They are discussed in Sect. 6. Sect. 7 summarizes the results and the conclusions.

2 Measurements

2.1 TWINS ENA Images

The NASA TWINS mission of opportunity (McComas et al., 2009a; Goldstein and McComas, 2013, Goldstein and McComas, 2018) obtains ENA images of the inner region of the Earth's magnetosphere. The instrument concept is described in McComas et al. (1998). Every 72 s with an integration (sweep) time of 60 s, full images are obtained. In this study, in order to obtain sufficient counts for the deconvolution process described in Sect. 2.2, the images are integrated over 15-16 sweeps. This means data is collected for ~15 min over an ~ 20 min time period. The energies of the neutral atoms span a range from 1-100 keV/amu. In the images used in this study, the energy bands are such that $\Delta E/E = 1.0$ for H atoms. In order to enhance the processed image, a statistical smoothing technique and background suppression algorithms described in detail in Appendix A of McComas et al. (2012) are employed. This combined approach is an adapted version of the statistical smoothing technique used successfully for IBEX (McComas et al., 2009b) data.

2.2 Ion Pressures

For the comparison with simulation results using the CIMI program (See Sect. 3.), the spatial and temporal evolution of equatorial ion partial pressure and pressure anisotropy are routinely obtained from the TWINS ENA images. To extract this information from the ENA images, the ion equatorial pitch angle distribution is expanded in terms of tri-cubic splines (deBoor, 1978). To fit the data and to obtain a smooth solution, the sum of normalized chi-squared and a penalty function derived by Wahba (1990) is minimized. The penalty function is what produces the smoothness of the result (in the sense of a minimum second derivative), and the normalized chi-square is what ensures that the calculated image corresponds to the measured ENA image. This means that the spatial structure obtained in the equatorial ion partial pressure distributions is no more than is required by the observations (Perez et al, 2004). In order to obtain pressures from the energy dependent ENA images, which are integrated over energy bands with widths equal to the central energy, e.g., 40 keV images are integrated from 20-60 keV, a technique using singular valued decomposition as described in Perez, et al., (2012, Appendix B) is employed. The energy range included in the partial pressures presented in this paper is 2.5-97.5 keV, i.e., the energy range observed by TWINS. It is to be noted that higher energies do make significant contributions to the total ring current pressure. (Smith and Hoffman, 1973)

In order to obtain the ion distributions from the ENA images, models for both the magnetic field and the exospheric neutral hydrogen density are required. In this study, we use the Tsyganenko and Sitnov (2005) magnetic field model and the TWINS exospheric neutral hydrogen density model (Zoennchen, et al, 2015).

We must also deal with the fact that there are two components to the ENA emissions: the energetic ions created in charge exchange interactions with neutral hydrogen in the geocorona, the so-called high altitude emissions (HAE), and those due to charge exchange with neutral oxygen at low altitudes (below ~ 600 km), the so-called low altitude emissions (LAE) (Roelof, 1997). The former are treated as optically thin emissions, and the latter with a thick target approximation developed by Bazell et al. (2010) and validated by comparisons with DMSP data (Hardy et al., 1984).

A full range of the ion characteristics obtained from the TWINS ENA images have been compared with in-situ measurements. Measurements of the spatial and temporal variations of the flux in specific energy bands from the Time History of Events and Macroscale Interactions during Substorms (THEMIS) (Angelopoulos, 2008) have been compared with ion flux obtained from the TWINS ENA images (Grimes et al, 2013; Perez et al, 2015). A similar comparison (Perez et al, 2016) has been made with measurements made on the Van Allen Probes (formerly known as the Radiation Belt Storm Probes (RBSP) A and B) (Mauk et al., 2013; Spence et al., 2013) by the Radiation Belt Storm Probes Ion Composition Experiment (RBSPICE) (Mitchell et al., 2013) instrument. Pitch angle distributions and pitch angle anisotropy have been compared with THEMIS observations (Grimes et al, 2013). Energy spectra have also been compared with THEMIS measurements (Perez et al, 2012). Partial pressure and anisotropy from TWINS have been compared with RBSP-SPICE-A (Perez et al, 2016) observations. While the in-situ measurements show more detailed temporal and spatial features, there is good agreement with the overall trends. Goldstein et al (2017) compared the TWINS ENA images with in-situ data from THEMIS and the Van Allen probes. They found evidence for bursty flows and ion structures in the plasma transport during the 2015 St. Patrick's day storm.

3 The CIMI Model

The CIMI model is a combination of the Comprehensive Ring Current Model (CRCM) (Fok et al, 2001b) and the Radiation Belt Environment (RBE) model (Fok, et al., 2008). The CRCM is a combination of the classic Rice Convection Model (RCM) (Harel et al, 1981) and the Fok kinetic model (Fok et al., 1993).

The CRCM simulates the evolution of an inner magnetosphere plasma distribution that conserves the first two adiabatic invariants. The Fok kinetic model solves the bounce-averaged Boltzmann equation with a specified electric and magnetic field to obtain the plasma distribution. It is able to include arbitrary pitch angles with a generalized RCM Birkeland current algorithm. The Fok model advances in time the ring current plasma distribution using either a self-consistent RCM field or the semi-empirical Weimer electric field model. A specified height-integrated ionospheric conductance is required for the RCM calculation of the electric field. The Hardy model (Hardy et al., 1987) provides auroral conductance. Losses along the particle drift paths are a key feature of the CIMI model. The CIMI pressure distributions utilized in this study cover an energy range from 75 eV to 133 keV.

Simulated results from CIMI or its predecessors have been tested against a variety of measurements from a number of satellite missions. Some examples are: (1) AMPTE/CCE (Fok et al., 2001b), (2) IMAGE ENA images (Fok et al., 2003), (3) Polar/CEPPAD (Ebihara et al., 2008), (4) IMAGE/EUV(Buzulukova et al., 2008), (5) TWINS ENA images (Fok, et al., 2010), (6) Radiation belt measurements and Akebono (Glocer, et al..,2011), (7) TWINS plasma sheet boundary conditions (Elfritz, et al., 2014), and (8) TWINS ENA images and Akebono (Fok et al., 2014). Using the Dessler-Parker-Schopke relation (Dessler and Parker, 1959; Schokpe, 1966), it has also been shown that the simulated CIMI pressures match well the observed SYM/H. (See Figure 9, Buzulukova et al., 2010). In this study, we present the first direct comparison between CIMI and TWINS ion partial pressure and anisotropy.

Important input to the CIMI simulations are the particles injected into the inner magnetosphere along the outer boundary of the simulation. In the simulations shown here, it has been assumed that the particles have a Maxwellian distribution with density and temperature determined by a linear relationship to the solar wind density and velocity respectively (Ebihara and Ejiri, 2000; Borovsky et al., 1998). A 2 hour time delay between the arrival of the solar wind parameters at the nose of the magnetopause and its effect on the ions crossing into the inner magnetosphere also has been assumed (Borovsky et al. 1998). The pitch angle distribution of the incoming ions is taken to be isotropic.

Results from simulations with the CIMI model using two different forms of the electric potential are compared in this investigation. One is the Weimer 2K empirical model (Weimer,

2001) and the other is a self-consistent electric potential from RCM.

4 The 7-10 September 2015 Storms

Figure 1 shows solar wind parameters and geomagnetic activity indices from the OMNI data service for 4 days, i.e., 7-10 September 2015. During this 4-day period, there were two SYM/H minima in succession. The first came early on 8 September 2015 after a 1-day long main phase on 7 September 2015. The minimum SYM/H was approximately -90 nT, so it was a relatively weak storm. There was a rapid recovery for approximately 3 hours coinciding with a sharp transition of B_z from negative, i.e., -8 or -9 nT, to positive, i.e., +18 or +19 nT along with a sharp transition of B_y from positive, i.e., +5 nT, to negative, i.e., -12 or -13 nT. There was also a sharp spike in the solar wind density at the inception of this first recovery phase. After the recovery was completed, there followed about a 12-hour period of near 0 nT SYM/H. The main phase of the second storm showed a relatively steady decline in SYM/H to a minimum near -110 nT in about 12 hours. The recovery from this second minimum was slow with a duration of about 1½ days. The second main phase and minimum corresponded to a slow swing of B_z back to negative and B_y to a slightly negative value. Also to be noted is the strong AE index, indicative of possible substorm activity during the main phases and early recovery of both minima. There is also some AE activity near the end of the second storm. During those same periods, the ASY/H index also had significant values during the main phase and early recovery of both minima. (See Figure 1.)

5 Results

5.1 Comparison of the Location of the Equatorial Ion Partial Pressure Peaks

Figure 2 shows the location of the equatorial ion partial pressure peaks as measured from the TWINS ENA images (green diamonds) and simulated by CIMI with both the Weimer 2K (red lines) and the RCM (orange lines) electric fields. Figure 2a is the radial location for the four days of the 07-10Sep2015 storms, and Figure 2b is the MLT location.

The radial positions of the partial pressure peaks for the CIMI simulations are similar, i.e., about 4 R_E, for both the Weimer 2K and the RCM electric potentials. The RCM results do show more variation. Many of the radial positions for the TWINS observations are also near 4 R_E, but others are at larger values. The MLT locations of the peaks are generally in the dusk/midnight sector. This is consistent with statistical analysis of proton fluxes from the database of the magnetospheric plasma analyzer (MPA) instrument aboard Los Alamos satellites at geosynchronous orbit (Korth et al., 1999). But the CIMI simulations, with both the Weimer 2K and RCM potentials, show a brief time early on 8 September 2015 where some of the peaks are in the midnight/dawn sector. Given the assumed 2 hour delay in the propagation of the solar wind parameters into the inner magnetosphere, this seems to correlate with a sharp swing in B_y shown in Figure 1. The TWINS observations show several instances of the partial pressure peaks being near midnight and in the midnight/dawn sector. As described earlier, ion flux peaks in this region have been seen from ENA images for very strong storms (Fok et al, 2003).

5.2 Comparison of Equatorial Ion Partial Pressure Peaks and Anisotropies at Specific Times

The following subsections will examine in detail a number of specific times during these two storms in order to address similarities and differences in the simulations with an empirical and a self-consistent electric field model and with observations. One apparent difference in what follows is the magnitude of the equatorial partial pressure for the three cases. The maximum on the colorbars for Figures 3-9 were chosen to be different for each time in order to emphasize the spatial dependence of the pressure distribution. The maxima for the two CIMI simulations are very similar, i.e., the RCM vary from 20-38 nPa and the Weimer 2K from 15-30 nPa. But the maxima of the TWINS peaks varyfrom 1-4 nPa, which is significantly smaller.

The magnitude of the ion intensities derived from the ENA images has been addressed in several previous comparisons with in-situ measurements. Vallat et al. (2004) compared Cluster-CIS (Réme et al., 2001) and IMAGE-HENA observations and found that for relatively strong fluxes, the agreement was excellent for two cases, but for another the ion flux determined from the ENA images was somewhat higher than the in-situ observations and in another it was significantly lower. Grimes et al. (2013) compared THEMIS (Angleopoulos, 2008) spectral measurements with spectra obtained from TWINS ENA images and found that the in-situ fluxes were a factor of 3 times greater than those obtained from the ENA images. Perez et al. (2016)

compared 30 keV ion fluxes obtained from TWINS ENA images with in-situ measurements by RBSPICE-A (Mauk et al., 2013) and found good agreement in both the average time dependent trend and in the magnitude. The in-situ measurements, of course, showed more structure given their much higher spatial and temporal resolution. Goldstein et al. (2017) analyzed data from THEMIS, Van Allen probes, and TWINS for a large storm to find that the ion fluxes obtained from the ENA images were generally lower than those from the in-situ measurements. They also found significant variations in the in-situ data. So while some part of the difference in the partial pressures obtained from TWINS measurements and CIMI simulations are due to the larger energy range included in the CIMI pressures, it is not the entire explanation. The issue of the absolute magnitude remains an important, unresolved issue, but the fluxes obtained from ENA images have been shown to reflect the global structure of the trapped ring current particles, and that is the emphasis in this study.

5.2.1 2200 UT 07 September 2015

Figure 3 shows the equatorial partial pressure profiles and the pressure anisotropy from the CIMI/RCM simulation, the TWINS observations, and the CIMI/Weimer 2K simulation at 2200 UT 07 September 2015. This was late in the main phase of the first storm (See Figure 1.). The radial locations of the peaks differ by less than 1 R_E. The MLT locations of the partial pressure peaks, however, differ by 3 hours in MLT. While the TWINS peak is near midnight, the CIMI peaks are well into the dusk/midnight sector with the CIMI/Weimer even closer to dusk. Results for the Weimer96 when compared with the RCM for a very strong storm showed even greater shielding for the RCM when compared to the empirical Weimer model (Fok et al., 2003). Note, however, that for this weaker storm, the MLT spread in the peaks of the partial pressure distributions do overlap. It is also to be noted that the TWINS results show more radial structure.

The pressure anisotropy shown in Figure 3 is defined as

$$A = \frac{P_{\perp} - P_{\parallel}}{P_{\perp} + P_{\parallel}}$$

with

$$\begin{Bmatrix} P_{\perp} \\ P_{\parallel} \end{Bmatrix} = 2\pi \int_{-1}^{+1} d\cos\alpha \begin{Bmatrix} \sin^2\alpha \\ 2\cos^2\alpha \end{Bmatrix} \left(\int_0^{\infty} dE \, \sqrt{2mE} \, F(E, n, \cos\alpha) \right)$$

where α is the ion pitch angle, E is the ion energy, n is the ion density, m is the ion mass and $F(E,n,\cos\alpha)$ is the number flux per unit area, energy, time, steradian. This definition is derived from Braginskii (1965) and is consistent with previous formulations, e.g., Lui et al. (1987).

The pressure anisotropy at the pressure peaks is somewhat perpendicular in all 3 cases. We also note a region of parallel anisotropy at R > 6-7 R_E from pre-midnight to dawn in all 3.

5.2.2 0400 UT 08 September 2015

Figure 4 shows results for 0400 UT 08 September 2015 in the same format. This was early in the rapid recovery phase of the first minimum in SYM/H. (See Figure 1.) The radial location of the partial pressure peaks again differ by less than 1 R_E. This time, however, all the peaks are in the dusk/midnight sector. Again the CIMI/Weimer 2K is closer to dusk than the CIMI/RCM pressure profiles. The TWINS peak is between the two simulations. The CIMI/Weimer 2K pressure distribution is more symmetric than the others even though the ASY/H shown in Figure 1 is > 50 nT. The region of parallel pressure anisotropy in the CIMI results does not appear in the TWINS results which are more nearly isotropic in general compared to the CIMI simulations.

5.2.3 1600 UT 08 September 2015

Figure 5 shows results for 1600 UT 08 September 2015 in the same format. This was during the period of near 0 nT SYM/H between the two storm minima. It was during a time period when both B_z and B_y are positive (See Figure 1.). Again the radial location of the partial pressure peaks are similar. The TWINS peak, however, has moved to the noon/dusk sector. It has continued to move westward from it positions in Figures 3 and 4. This could be the classic drift due to magnetic field gradient and curvature as originally observed in IMAGE/HENA ENA images by Brandt et al., (2001). In contrast to the TWINS pressure profile, the CIMI pressures reflect a nearly symmetric ring current. While ASY/H was relatively low at this time, it did show a small peak (See Figure 1.). Both the CIMI/RCM and the CIMI/Weimer 2K results show a region of parallel pressure anisotropy at large radii that almost circles the Earth. The TWINS results show only perpendicular pressure anisotropy.

5.2.4 0200 UT 09 September 2015

Figure 6 shows results for 0200 UT 09 September 2015 in the same format. This is early in the main phase of the second minimum in SYM/H (See Figure 1.). The TWINS equatorial ion partial pressure peak is at a larger radius and in the midnight/dawn sector in contrast to the CIMI results where the peaks are in the dusk/midnight sector. There is considerably more spatial structure in the TWINS results. The strongest TWINS peak extends well into the dusk/midnight sector with a region near the same location as the CIMI peaks and with another at a larger radius in the dusk/midnight sector. There is an even larger difference in the pressure anisotropy. The parallel region at large radii in the CIMI result is even more parallel but is again absent in the TWINS result. The small intense parallel region at very small radius in the TWINS plot is a region of very low flux and therefore not a reliable ratio. At this time, the AE index was rising sharply as was the ASY/H index (See Figure 1.).

5.2.5 0400 UT 09 September 2015

Figure 7 shows results for 0400 UT 09 September 2015 in the same format. This was just 2 hours later than the time shown in Figure 6. It was near the end of the main phase of the second minimum in SYM/H (See Figure 1.). Again the TWINS peak is in the midnight/dawn region whereas the CIMI peaks appear in the dusk/midnight region, but the radial location is very nearly the same. This time, however, the TWINS peak extends past dawn and not into the pre-midnight region. Even though the MLT location of the CIMI/RCM and the CIMI/Weimer 2K peaks are nearly the same, the CIMI/Weimer 2K maximum extends to almost noon. The pressure anisotropy shows features very similar to those seen 2 hours previously (See Figure 6.) .The AE index has been at fairly high values for about an hour and the ASY/H index is beginning to rise sharply again (See Figure 1.).

5.2.6 1800 UT 09 September 2015

Figure 8 shows results from 1800 UT 09 September 2015 in the same format. At this time SYM/H (See Figure 1.) shows that the second storm was a few hours into a slow recovery. There are 4 distinct peaks in the TWINS equatorial ion partial pressure distribution. The highest is at large radius, about 7 R_E, in the dusk/midnight sector. There is another lower peak, also at large radius in the noon/dusk sector. There are two peaks at a similar radius as the CIMI peaks. This interval is an example of multiple peaks in the ring current that have been inferred from in-situ measurements (Liu et al., 1987), and seen in analysis of ENA images (Perez et al., 2015). The parallel pressure anisotropy in the CIMI results is again present, but it is smaller and weaker than at previous times. Again TWINS does not show this feature.

5.2.7 1700 UT 10 September 2015

Figure 9 shows results from 1700 UT 10 September 2015 in the same format. At this time the second storm was well into its slow recovery, SYM/H was beginning a small dip, there was a peak in the AE index, and ASY/H had a weak peak. (See Figure 1.) The partial pressure profiles for CIMI/RCM and CIMI/Weimer 2K are symmetrical with a peak in the dusk/midnight sector. The TWINS partial pressure peak is closer to dusk. This interval is in contrast to results at earlier times in the storm. The TWINS partial pressure peak is at a larger radius, and there is very little flux in the dawn/noon sector. The CIMI pressure anisotropies again show a region of strong parallel pitch angles that is not seen in TWINS.

6 Discussion

Injections from the plasma sheet are thought to be the primary source of ring current protons in the inner magnetosphere, i.e., those that are observed by TWINS. Electric and magnetic fields determine the ultimate path of the injected ions, i.e., whether they reach locations close enough to the Earth where the magnetic gradient and curvature drifts are strong enough to exceed the electric drift forming the ring current or whether they drift out to the magnetopause. The locations of the partial pressure peaks from the CIMI/RCM and the CIMI/Weimer 2K simulations and the TWINS observations during the 4-day period, 07-10 September 2015, show that the peaks are usually in the dusk/midnight sector. (See Figure 2b) This phenomenon is consistent with analysis of data at geosynchronous orbit (Birn et al., 1997). Nevertheless the TWINS observations show partial pressure peaks that are often at larger radii than the CIMI simulations, even when they are in the dusk/midnight sector (See Figure 2a.). The fact that the

CIMI/Weimer peaks are generally closer to dusk than the CIMI/RCM. (See Figure 2b.) is consistent with simulations reported by Fok, et al. (2003). The TWINS MLT locations are closer to midnight and in the midnight /dawn sector more frequently than the CIMI results. This suggests that there are often enhanced electric shielding and effects from localized and short time injections that are not present in the CIMI simulations. To understand how the electric shielding works to affect the paths of the injected particles, we note that the convection electric field from the solar wind is mapped into the magnetosphere along open field lines into the polar ionosphere. It is then shielded from penetrating to lower latitudes and therefore further into the inner magnetosphere by the Birkeland region 2 currents driven by pressure gradients in the ring current. During geomagnetic storms when there is a sharp turn in the z-component of the interplanetary magnetic field (IMF) from negative to positive (See row 2 of Figure 1.), the accompanying electric field in the ionosphere associated with the Region 2 currents can produce what is referred to as over-shielding. See for example Jaggi and Wolf (1973). There are also neutral disturbance dynamo electric fields in the ionosphere that affect electric shielding. Localized and short time injections may contribute to the complexity of these effects.

Looking in detail reveals an even more complex story. Figures 3-9 show comparisons of the partial pressure profiles during different phases of the storms. In the main phase of the first storm (See Figure 3.), while there is a significant AE index and ASY/H asymmetry (See Figure 1.), the observed TWINS peak is at midnight while the simulated peaks are more toward dusk. During the rapid recovery phase of the first storm, (See Figure 4.) when the AE index is smaller (See Figure 1.), the observed and simulated partial pressure peaks are at approximately the same radius, and all are in the dusk/midnight sector. During the period between the two storms (See Figure 5.) when there is very little geomagnetic activity, i.e., SYM/H near 0 nT (See Figure 1.), the observed partial pressure peak has drifted more westward than the simulated peaks, even going past dusk (See Figure 5.). Another feature to note is the symmetry of the ring current in the CIMI simulations whereas the TWINS observations show a gap in the dawn/noon sector. The ASY/H index shows a small peak at this time (See Figure 1.) This suggests time dependence in the electric and magnetic fields that is not present in the CIMI simulations.

It is in the second storm (Figures 6-8) that the TWINS observations begin to show more spatial and temporal structure than the CIMI simulations. In Figure 6, early in the main phase, the TWINS observations show the main partial pressure peak near 6 R_E and 3 MLT while the simulated peaks are near 4 R_E and 20 MLT. But there is also a strong observed pressure region in the same area as the simulated peaks. Just 2 hours later, the simulated pressure shows little change, but the observed main peak extends farther eastward, and the relative pressure in the dusk/midnight region has weakened relative to the main peak. Fourteen hours later in the recovery phase of the second storm, the simulated peaks have not changed significantly, whereas the TWINS observed peaks are dramatically different (See Figure 8.).. There are 4 pressure peaks. The strongest peak is at 7 R_E and just westward of midnight. At smaller radii, there is a weaker peak near the location of the simulated peaks as well as one on the dawn side past midnight. There is another weaker peak at large radius near noon. It should be noted that there is strong AE activity and that ASY/H has significant values during this period (See Figure 1.). This activity suggests that there may be variations in the electric and magnetic fields produced by spatial and time dependence of the location of the ion injections that are not present in the CIMI simulations.

The increased structure in the partial pressure distributions as observed by TWINS is especially dramatic during the recovery phase of the second storm. (See Figure 8.) There is strong AE activity and the largest values of ASY/H during this period. In the late recovery of the second storm (See Figure 9.), the CIMI simulations show a symmetric ring current as expected (Pollock et al., 2001). The TWINS results are not symmetric and have a peak at large radius in the dusk/midnight sector. There is some AE activity and a rise in the ASY/H index at this time.

Figures 3-9 also show comparisons of the pressure anisotropy during the different phases of the storm. The pressure anisotropies at the partial pressure peaks are generally in good agreement among the 3 results presented here, i.e., the pitch angle distributions are more perpendicular than parallel. The CIMI simulations, however, show a consistent region of parallel anisotropy at radii outside the pressure peak. The degree to which the pitch angle distributions are more parallel increases until the early recovery phase of the second storm (See Figure 8.) where it weakens but then strengthens again in the late recovery phase. This feature is seen by TWINS only in the main phase of the first storm (See Figure 3.) and perhaps very faintly in the early recovery phase of the second storm. (See Figure 8.) The ions that are injected at the boundary of the CIMI simulations, located at 10 R_E for those shown here, have an isotropic pitch angle distribution. As they are accelerated while conserving the first adiabatic invariant to enter the region observed by TWINS, i.e. an outer radius of 8 R_E, their pitch angle distributions become parallel because the energy increase exceeds what can be absorbed in the perpendicular pitch angles while still conserving the first adiabatic invariant. One mechanism for reducing the parallel anisotropy is wave-particle interactions which are not included in the CIMI simulations..

Another possible contributing factor to the differences between the observations and simulations is the input to the CIMI model used in these simulations. Following Fok et al.(2014), the ion distribution at the boundary of the CIMI simulations in this study is an isotropic, Maxwellian distribution at a radius of 10 R_E at all MLT. The density and temperature of the Maxwellian is taken to have a linear relation to the solar wind density and solar wind velocity respectively (Borovsky et al., 1998; Ebihara and Ejiri, 2000). This produces a relatively smooth time variation in the input which has been shown to be successful in matching the general features of SYM/H (Buzulukova et al., 2010), but does not match the more rapid variations as a function of time. It has also been shown that varying the spatial dependence of the input along the boundary can have a significant effect on the location of the pressure peaks (Zheng et al., 2010). Likewise Buzulukova et al. (2010) showed that input of non-isotropic pitch angle distributions can affect the comparison between the CIMI simulations and the ENA observations.

There is significant experimental evidence for temporal and spatial variations in the injection of ions into the trapped particle region of the ring current (e.g., Birn et al.., 1997; Daglis et al., 2000; Lui et al., 2004). Bursty bulk flows associated with near-Earth magnetic reconnection events have been frequently observed in the magnetotail (Angelopoulos et al., 1992). These fast flows have been observed to have a 1-3 R_E width in the dawn-dusk direction (e.g., Angelopoulos et al., 1996; Nakamura et al., 2001; Angelopoulos et al., 2002). Magnetic flux ropes flowing

Earthward have also been observed (e.g., Slavin et al., 2003; Eastwood et al., 2005; Imber et al., 2011). Short time, spatially limited injections into the inner magnetosphere have also been seen in 3D hybrid simulations. (e.g. see Lin et al., 2014.) Thus it is reasonable to suppose that the additional spatial and temporal structure in the partial pressure profiles observed during this storm is due to effects not yet incorporated into the simulations.

Buzulukova et al. (2008) combined the Comprehensive Ring Current Model (CRCM) (Fok et al., 2001) and the Dynamical Global Core Plasma Model (Ober et al., 1997) to model features of the plasma sphere observed by the Extreme UltraViolet (EUV) instrument on the Imager for Magnetosphere-to-Aurora Global Exploration (IMAGE) (Burch, 2000) on 17 April 2002. They found that injections from the plasma sheet that were localized in magnetic local time (MLT) explained observed undulations of the plasmasphere. Some features of an inductive electric field were included through the use of a time dependent magnetic Tsy96 (Tsyganenko and Stern, 1996) magnetic field model.

Likewise, Ebihara et al. (2009) compared CRCM simulations with midlatitude Super Dual Auroal Radar Network (SuperDARN) Hokkaido radar observations of fluctuating iononspheric flows on 15 December 2006. Using input from geosynchronous satellites to model the temporal and spatial variations of the plasma sheet input to the inner magnetosphere, they were able to show that the resulting pressure variations in the ring current were responsible for field aligned currents and matched the dynamics of the observed subauroral flows. The results from the CRCM also showed multiple pressure peaks inside of 4 R_E. This is indicative of a strong connection between the dynamics of the ring current pressure distribution and the rapid temporal characteristics of the subauroral plasma flow during a geomagnetic storm.

The comparisons between the observations and the simulations presented here give a view not available from in-situ measurements. To further elucidate this phenomenon, we present in Figure 10 the paths of particles injected into the inner magnetosphere calculated using the CIMI simulations that provide additional support for concluding that the observations may show effects from enhanced electric shielding and localized and short time injections. The focus is upon the time 1800 UT on 9 September 2015 during the second storm. As shown in Figure 8, the TWINS observations show multiple peaks in contrast to the single peak in the CIMI simulations. For each of the 4 partial pressure peaks observed by TWINS, we show the energy spectrum (left column) and the paths of particles that reach the location of the pressure peaks (right column). The energy spectra show two energy maxima, one below 20 keV and the largest maxima above 40 keV. The ion paths are calculated with the CIMI model using the RCM fields. The path shown is of a particle with an energy of 46 keV when it reaches the respective pressure peaks, i.e., the energy at the maximum of the energy spectra shown in the left hand column. The TWINS partial pressure configuration from Figure 8 is repeated in gray scale so as to highlight the paths. In each case the pressure peak is shown by a black square. Along the path there are stars every 10 minutes. The color of the stars indicate the ion energy as it moves along its path. (See color bar.)

For Peak 1, the 46 keV particle enters at 10 R_E in the midnight/dawn sector. The time from injection to reaching this peak in the outer magnetosphere is approximately 20 minutes. For

Peak 2, which is at a smaller radius, a 46 keV ions arrives at the peak from the dawn/midnight sector after approximately 2 ½ hours. This peak observed by TWINS is very near the pressure peak that appears in the CIMI simulations. (See Figure 8.) Peak 3 is at a similar radius as Peak 2, but it is on the dawn side of midnight. The path of a 46 keV particle followed backwards in time from this peak location does not show an injection location after completing nearly 3 orbits of the Earth in approximately 12 hours. This partial pressure peak observed by TWINS may not be consistent with the RCM fields in the CIMI model. Peak 4 is in the noon/dusk sector. A 46 keV particle reaches this peak after approximately 3 ¾ hours and 1 orbit of the Earth. It enters the inner magnetosphere in the same sector, i.e., the midnight/dawn sector, as the particle that reached the location of Peak 1, but it was injected much earlier. The different locations and times of the entrance of the ions at the peaks of the energy spectra of the 4 pressure peaks 1, 2, and 4 observed by TWINS at 1808 UT on 9 September 2015 suggest spatial and temporal variations in the injections from the plasma sheet. The fact that the calculated path for Peak 3 does not show an injection may indicate variations in the fields not captured in the models.

7 Summary and Conclusions

We have presented, for the first time, direct comparisons of the equatorial ion partial pressure distributions and pitch angle anisotropy obtained from TWINS ENA images and CIMI simulations using both an empirical Weimer 2K and the self-consistent RCM electric potentials for a 4-day period, 7-10 September 2015. There were two moderate storms in succession during this period (See Figure 1.). In most cases, we find that the comparison of the general features of the ring current in the inner magnetosphere obtained from the observations and simulations are in agreement. Nevertheless, we do see consistent indications effects of enhanced electric shielding and localized and short time injections from the plasma sheet in the observations. The simulated partial pressure peaks are often inside the measured peaks and are more toward dusk than the measured values (See Figure 2.). There are also cases in which the measured equatorial ion partial pressure distribution shows multiple peaks that are not seen in the simulations (See Figure 8.). This occurs during a period of intense AE index. The observations suggest time and spatially dependent injections from the plasma sheet that are not included in the simulations. The paths of the ions that enter the inner magnetosphere calculated with the CIMI model using the self-consistent RCM fields support this interpretation.

The simulations consistently show regions of parallel anisotropy spanning the night side between approximately 6 and 8 R_E (See Figures 3-9.). This is thought to be a result of the increasing energy of the particles as they come enter the simulation region at 10 RE with isotropic pitch angle distributions. The particles are entering regions of stronger magnetic field so conservation of the first adiabatic invariant requires the perpendicular velocity to increase, but it is not adequate to accommodate the increase in energy. So the parallel velocity must increase. Nevertheless the parallel anisotropy is seen in the observations only during the main phase of the first storm. Localized and short time injections may produce ions that are injected with perpendicular pitch angle distributions that would result in the observed nearly isotropic pressure anisotropy.

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Figure Captions

Figure 1. The solar wind parameters and geomagnetic indices for the two storms during the period 07-10 September 2015. The data is from the OMNI data base (https://omniweb.gsfc.nasa.gov/html/omni_min_data.html).

Figure 2. Plot of the ion equatorial pressure peak as a function of time during the 4-day period 07-10 September 2015. (a) the radial location and (b) the MLT location. The green triangles mark the locations obtained from the TWINS ENA images, the red line from the CIMI/Weimer simulations and the orange line from the CIMI/RCM simulations.

Figure 3. The ion equatorial pressure (first row) and pressure anisotropy (second row) for 2200 UT 07 September 2015 from the CIMI/RCM simulations (first column), from the TWINS ENA images (second column), and the CIMI/Weimer simulations (third column). The stars mark the location of the peaks.

Figure 4. The ion equatorial pressure and pressure anisotropy for 0400 UT 08 September 2015 in the same format as Figure 3.

Figure 5. The ion equatorial pressure and pressure anisotropy for 1600 UT 08 September 2015 in the same format as Figure 3.

Figure 6. The ion equatorial pressure and pressure anisotropy for 0200 UT 09 September 2015 in the same format as Figure 3.

Figure 7. The ion equatorial pressure and pressure anisotropy for 0400 UT 09 September 2015 in the same format as Figure 3.

Figure 8. The ion equatorial pressure and pressure anisotropy for 1800 UT 09 September 2015 in the same format as Figure 3.

Figure 9. The ion equatorial pressure and pressure anisotropy for 1700 UT 10 September 2015 in the same format as Figure 3.

Figure 10. Paths of 46 keV particles, the energy of protons at the maximum flux (See left column.) that reach the 4 pressure peaks observed by TWINS as shown in Figure 8. The observed pressure is shown in grey scale. The locations of the peaks are shown by black squares. The energy of the particle is indicated by the color of the stars that are spaced 10 minutes apart. The units of the color bars are keV. The energies span the range of the particle energies along their paths.